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EXPERIMENTAL RESEARCH ON THE CONDENSATION PROCESS IN A SUPERSONIC FLOW

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EXPERIMENTAL RESEARCH ON THE CONDENSATION PROCESS IN A SUPERSONIC FLOW

G.A. Mukhachev and Yu.P. Metelin

ABSTRACT: Experimental research is conducted on the process of spontaneous condensation of steam in a plane Laval nozzle. Measurement is made of the static pressure distribution along a conduit. The application of the optical method facilitates the determination of the dimension and number of particles in the liquid phase. The law of drop formation as a function of time is presented. Comparison is made between the obtained results and the classical theory of nuclear condensation.

More and more attention has recently been paid to condensation processes of steams, the components of air and alkali metal vapors as they flow through convergent channels. /31*

Despite the large amount of research done both in our country and abroad, there is not yet a reliable method for calculating these processes which can correctly reflect the physical pattern of the process and yet be simple. A similar position is explained by the almost total absence of experimental data on the kinetics of condensation.

Reference [1], the dissertations of G.V. Tsiklauri[1] and G.A. Saltanov[2], and also the research of G. Gyarmathy [2] showed that there was a significant influence of the rate of the expansion process on the value of the supercooling which precedes the beginning of steam condensation. However, the actual mechanism of spontaneous condensation (the number and dimensions of the forming drops, their development rate, etc.) has not yet been investigated experimentally.

To solve this problem the authors developed a research procedure and built an experimental apparatus. In our work we used the optical method, which at the present time is the most rational in problems of this type. Theoretical analysis and preliminary investigations, made earlier on experimental equipment based on a Kazanskaya TETs-1, showed that all the known optical methods used

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[1] G.V. Tsiklauri. Cand. Dissertation, Moscow Power Institute, 1964.

[2] G.A. Saltanov. Cand. Dissertation, Moscow Power Institute, 1965.

* Numbers in the margin indicate pagination in the foreign text.

in practice for studying dispersion media [3-5] were inapplicable, in this case due to the extremely small size of the particles when their concentration was insignificant, and also due to the actually attained dimensions of the light-diffusing volume.

To investigate these media we propose in this article a method based not on the determination of the difference of two large measured values, i.e., the intensity of the incident light beam and the light beam passing through the dispersing medium, as in references [4,5] and the dissertation of S.M. Bazarov[3], which, in this case, is very small. Rather this method is based on a measurement of only one value, i.e., the intensity of the light diffused by the medium at a particular angle. In our experiment we measured the intensity of light diffused at an angle of 90° to the direction of the propagation of the incident beams. By comparison of the measured intensity with the intensity of the molecular diffusion of specially chosen standard fluids we determined the coefficient of dispersion R_{90}, whose value depends on the conditions under which the experiment is conducted and is a function only of the light-diffusing characteristics of the medium which, in this case, are the dimension and number of drops and the index of refraction of the drop material. /31

Figure 1 shows a fundamental schematic of the experiment. Superheated steam from the last stages of the turbines with a pressure of 8 bar and a temperature $t = 250°$ C enters through valve V_1 and the measuring diaphragm D_{st} into the cooler C from which it is directed to the entrance receiver (1) where the velocity fields are balanced, the pulsations decreased and the flow decelerated. The investigated nozzle is attached to the flanges of the entrance receiver (1) and the exit receiver (3) from which the steam is sucked by an ejector, providing a constant pressure at the exit of 0.3 bar. To conduct the optical measurements, the visual observation and photography of the process of steam efflux, the plane nozzle had transparent side walls (2) and a transparent upper wall made of K108 optical glass. The seals were made air-tight using thin teflon gaskets, epoxy resin and "Hermetic" paste. The profile of the nozzle was determined by the shape of the steel oxidized lower bushing (16). The axis of the optical instrument (7) was aligned perpendicular to the longitudinal axis of the nozzle. The instrument was automatically moved across the nozzle using a coordinate spacer (8) by an electric motor (9). The optical instrument itself has three components: an illuminator (10), a receiver for diffused light (11) and a receiver for passing light, (12) tightly sealed by a bracket (13). The latter is on runners which move along the base (15) of the coordinate spacer (8).

Visual observations were made using the illuminator (6) which directs a parallel light beam along the axis of the nozzle. To

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[3] S.M. Bazarov. Author's abstract, Cand. Dissertation, Leningrad, 1967.

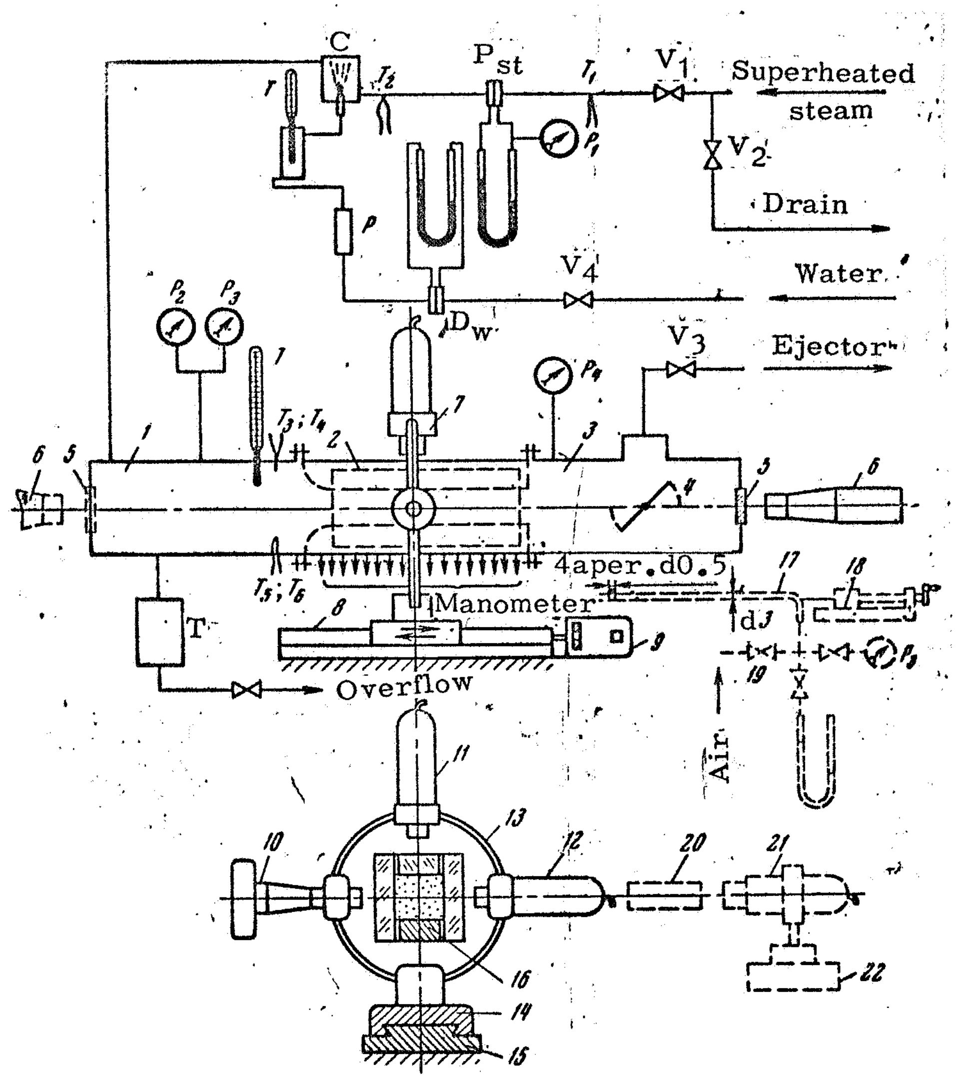

Fig. 1. A Schematic of the Experimental Equipment.

protect the cover glass from erosion by drops of moisture, we installed a screen (4). When we were making observations and photographic study, the screen was aligned along the axis of the nozzle. /32

During the experiments we measured the following parameters: the flow rate of the superheated steam (through diaphragm D_{st}) and cooling water (through diaphragm D_w), using a volumetric flowmeter P, the amount of moisture separated out on the walls of the supply pipe and receiver (1) (by the measuring tank T). Pressure and temperature of the steam in the receiver (by samples) by the manometers P_2 and P_3, the thermometer T and four chromel-copel thermocouples T_3 - T_6. We measured the static pressure along the conduit and made optical measurements.

The static pressure along the nozzle was sampled through apertures with a diameter of 0.9 mm placed at intervals of 2.5 mm in the lower bushing (16). The pressure was measured by mercury manometers placed on one panel. In the second phase of our work the static pressure was measured by a probe (17), moved along the rectilinear upper wall of the nozzle. The probe was a tube with a diameter of 3 mm made of stainless steel sealed at the end. To sample the pressure in the tube, four holes were drilled (in one cross section with diameter of 0.5 mm). The probe was moved using a coordinate spacer (18). The static pressure was measured by mercury and spring-loaded (P_3) manometers. Before measuring, the probe and the entire measuring line were purged with compressed air from valve (19). During the probing operation the illuminator (6) was aimed from the direction of receiver (1) (the dotted line).

Optical measurements were made at night time, in total darkness. Special attention was paid to the cleanliness of the optical components and the windows of the nozzle. Before beginning the experiments the entire steam line was purged for a day with compressed air. To prevent the accidental incidence of steam of the transparent parts of the optical instrument, we set up a screen of dry compressed air between the nozzle and the components of the instrument. The optical measurements were reduced to measuring the intensities of the passing and diffused light[4], formed in receivers (11) and (12) by FEU-19M type photomultipliers into an electric signal. The power supply to all the instruments including the autotransformer of the heating current of the illuminator lamp (10) was accomplished from a ferroresonance stabilizer. Voltage was supplied to the electrodes of the photomultiplier from a type VS-22 high voltage stabilized rectifier through a voltage divider. The photocurrent of the passing light receiver (12), which in the absence of noticeable weakening of the light rays by the diffusion medium serves to keep the incident light flux constant, is detected by an F-359 compensating amplifier and recorded on an EPP-09 recording potentiometer. The photocurrent of the diffused light receiver (11) was recorded by a recording electronic EPPV-60MZ potentiometer with a high impedance input section. To keep the heating current of the illuminator lamp constant we used an N-372 recording instrument. /32

Visual observations and photographs of the process of steam efflux from nozzles of various profiles, made both in the course of our work and earlier efforts, allowed us to present a qualitative picture of the process of spontaneous condensation. Thus, in all operating regimes of the nozzle examined here (cf. Fig. 2) the zone of moist steam was fixed by the appearance of characteristic lumines-

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[4] In certain particular cases of the operation of the nozzle (for example in the presence of roughly dispersed moisture at the entrance to the nozzle) the optical instrument (7) allowed us to take measurements by the least angle method [3]. To do this the receiver of passing light (12) was replaced by the unit of a long-focus lens (20) and the movable unit of a photomultiplier (21), moved by the coordinate spacer (22).

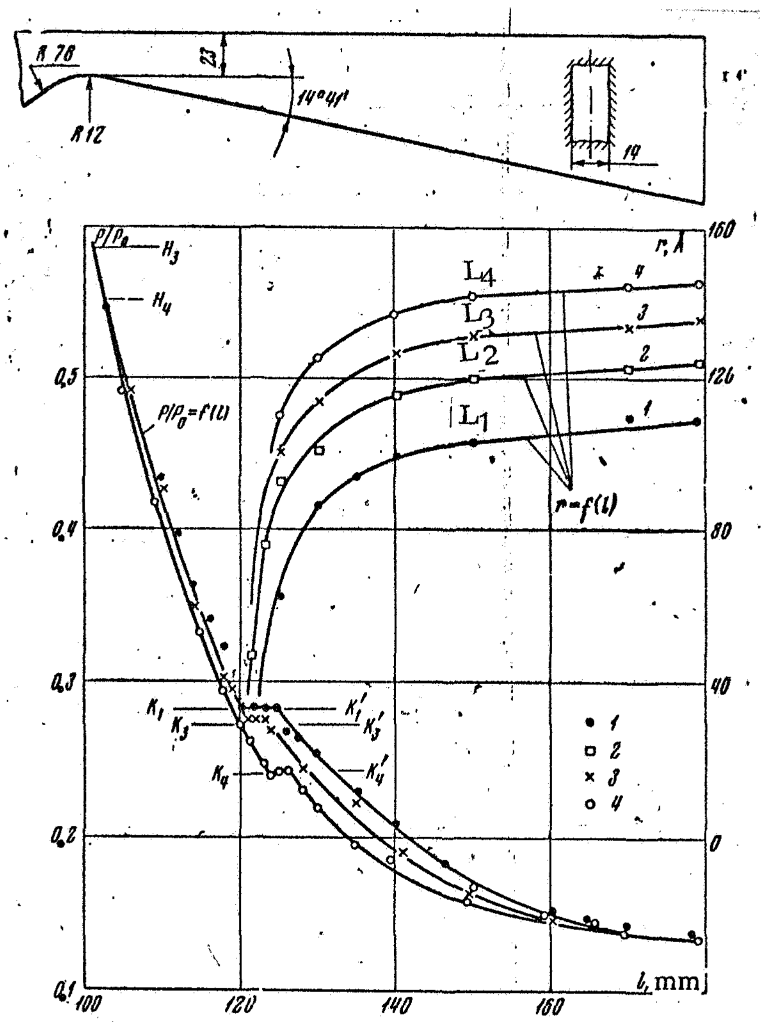

Fig. 2. The Change in the Static Pressure and the Dimension of the Drops of Moisture Along the Length of the Nozzle: 1 - P_0 = 2.39 bar, t_0 = 154° C; 2 - P_0 = 2.84 bar, t_0 = 168° C; 3 - P_0 = 3.16 bar, t_0 = 171° C; 4 - P_0 = 3.63 bar, t_0 = 180° C.

scence, whose color and intensity vary along the nozzle and are functions of the initial parameters of the steam and of the parameters, corresponding to the saturation state. With low initial parameters (P_i = 0.7 - 1.5 bar) we observed a scarcely perceptible light-blue luminescence. The boundary between the zones of supercooled and moist steam was poorly defined. As the initial pressure increases, the intensity of the luminescence in a given cross section of the nozzle increases drastically, and the indicated boundary becomes more distinct. In all regimes the boundary was practically planar, perpendicular to the axis of the nozzle. We should mention in passing that earlier attempts at observing the process of spontaneous condensation in passing light (the light source, the observer and the observed cross section were all in a straight line) and also investigations using the shadow method did not yield any positive results. Not one of these methods allowed us to divide the /3 zone of moist steam from the zone of dry and supercooled steam.

Measurements of the static pressure (Fig. 2) showed that the beginning of condensation, as was also shown in [1, 2] and in the dissertations of G.B. Tsiklauri and G.A. Saltanov, is characterized by a change in the pressure curve $P/P_0 = f(l)$. In all regimes the pressure curve in the initial stage of condensation forms a kind of step $K - K'$, whose shape, extent and position for the investigated nozzle vary with the values of the inital superheating and the parameters corresponding to the saturation state (the S points on the pressure curve).

As in [2], in our work the step $K - K'$ could have been vertical or had an upward slope. As a rule, with large values of the parameters at the entrance (P_i = 3-4 bar) in the initial condensation zone, the pressure curve rises somewhat and the length of the step is small; with small values of the parameters (P_i = 0.7 - 2 bar), the step $K - K'$ is horizontal or only slightly sloped downstream and its length is greater. With an increase in the initial superheating, as was shown in the reference of G.B. Tsiklauri and M.Ye. Deych [1] and G.A. Saltanov, the beginning of condensation shifts to the exit cross section of the nozzle.

Measurements of the intensity of diffused light I_{90} allowed us to determine the diffusion coefficient R_{90}, determined by the relationship

$$R_{90} = \frac{I_{90}}{I_0} \frac{L^2}{V}, \tag{1}$$

where I_0 is the intensity of the incident light, V is the diffusing volume, L is the distance from the center of the diffusing volume to the light receiver (photomultiplier).

Using the Rayleigh formula for the intensity I of light, diffused on a small particle,

$$I_\beta = I_0 \frac{16\pi^4 r^6}{\lambda^4 \cdot L^2} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 \left(\frac{1 + \cos^2 \beta}{2} \right), \tag{2}$$

where λ is the wavelength of the diffused light, m is the index of refraction of the particle material, β is the angle of observation; r is the radius of the particles, we may obtain the relationship between the dispersion coefficient and the characteristics of the dispersion medium:

$$R_{90} = 1{,}915 \cdot \frac{\pi^4}{\lambda^4} S r^3 \left| \frac{m^2 - 1}{m^2 + 2} \right|^2, \tag{3}$$

where S is the volume concentration of the liquid phase.

It is clear from formula (3) that the diffusion coefficient is closely related to the dimension of the drop $R_{90} \sim r^3$.

The expression for the volume concentration of the fluid phase in vapor steam has the form

$$S = \frac{y \cdot v_l}{v_{st}}, \tag{4}$$

where y is the degree of moisture of the steam; v_l and v_{st} are, respectively, the specific volumes of liquid and vapor steam.

The number of drops in a unit volume is determined by:

$$z = \frac{y \cdot v_l}{v_{st}} \frac{1}{v_d}, \tag{5}$$

where v_d is the volume of a drop.

Figures 2-5 show the results of interpretation of the experimental data using (3) - (5). The values of the degree of moisture /3:

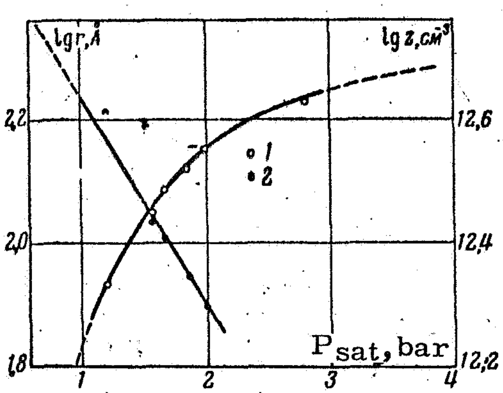

Fig. 3. The Dimension and Number of Drops as a Function of the Saturation Parameters: (1) $r = f(P_{sat})$; (2) $z = f(P_{sat})$.

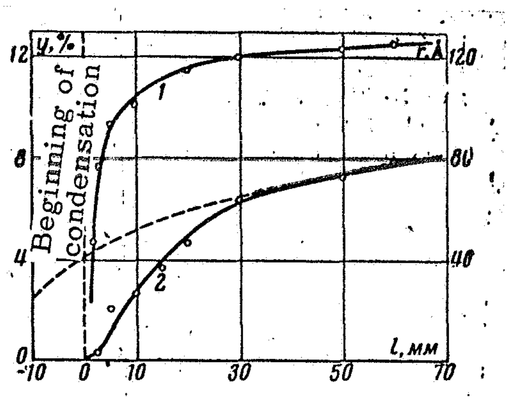

Fig. 4. The Change in the Mass Portion of the Liquid and the Dimension of the Drops Along the Length of the Nozzle: P_0 = 2.84 bar; t_0 = 168° C: (1) $r = f(e)$; (2) $y = f(e)$.

y and the volume of steam v_{st} were determined from the results of measurements of the static pressure in the zone of developed condensation (in the region of small pressure gradients near the exit cross section of the nozzle). The number of drops in this region was determined from formula (5). Subsequent interpretation of the experimental data was made on the assumption that the number of drops per unit mass was constant with a given operating regime of the nozzle.

Based on the measurements of the dispersion coefficient of the condensed steam, we chose the following pattern for the process of spontaneous condensation: (1) individual groups of molecules, capable of further consolidation, are formed in the supercooled steam as a result of fluctuations; (2) condensation of the steam takes place spontaneously on these nuclei upon reaching definite supersaturation, while for a short period of time $\tau \approx 10^{-6}$ sec rather large drops form whose dimensions are 1 - 1.5 orders of magnitude larger than the initial nuclei; in this case there is a sharp decrease in the supersaturation of the steam; (3) further condensation takes place on these drops with minimum supersaturation (supercooling).

In interpreting the experimental data we did not take into account the effects of coagulation and fractionation in view of the large distance between drops (about 10^{-4} cm) and their small lateral velocity component.

As we can conclude from Figure 2, there are very small drops at the initial moment of condensation. Extrapolation of the curves $r = f(l)$ to the abscissa of the point K yields the value r = 5-10 Å. For a short period of time the drops grow to dimensions of 50-100 Å. The highest growth rate of the drops is observed in the zone $K - K'$, then the growth rate decreases and, beginning at some point L at a distance $l \cong 150$ mm, the growth of the drops is roughly linear.

According to the Kelvin-Helmholtz formula

$$\ln P / P_\infty = 2\sigma v_1 / r \cdot R \cdot T, \qquad (6)$$

where σ is the coefficient of surface tension; R is the gas constant.

The dimensions of the drops at the beginning of the linear part of the curve $r = f(l)$ correspond to supersaturation P/P_∞ = 1.1-1.01, i.e., the pressure and temperature of the drop and the surrounding steam are equal and correspond to the parameters of the plane boundary dividing the phases. In this case with moderate longitudinal pressure gradients and comparatively small dimensions /32 of the drops (less than the length of the mean free path of molecules), the parameters of the drop, as was shown in reference [6], will almost instantaneously follow the change in the parameters of the steam, i.e., the condensation process is an equilibrium one.

The optical method used in our work also allowed us to observe the influence of the parameters corresponding to the saturation state, on the kinetics of condensation. It appeared that the dimension of the drops in the zone of developed condensation increased significantly as the saturation pressure P_{sat} increased (Fig. 3). The number of drops per unit volume decreased. Thus for the point L which marks the beginning of the linear part of the curve $r = f(l)$, with $P_{sat} = 0.5$ bar, $r = 3.8 \cdot 10^{-7}$ cm and $z = 6.3 \cdot 10^{12}$ $1/cm^3$; with $P_{sat} = 10$ bar, $r = 2.1 \cdot 10^{-6}$ cm and $z = 3 \cdot 10^9$ $1/cm^3$.

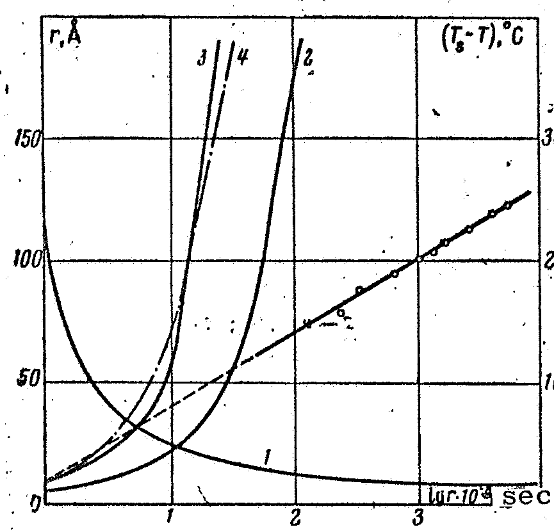

Fig. 5. The Dimension of the Drop and the Value of Supercooling as a Function of Time from the Moment of Condensation: $P_0 = 2.84$ bar, $T_0 = 168°C$: (1) $(T_s - T) = f(\tau)$; (2) According to (7); (3) According to (8); (4) According to (9).

One of the unsolved problems of the kinetics of condensation of supersaturated steam is the question of the quantity of liquid formed in the initial stage of spontaneous condensation. The curves in Figure 4 were constructed from the results of the experiments. These curves show the dimension of the drops r and the moisture level y as a function of the distance traveled by the steam from the initial point of condensation (point K in Fig. 2). For comparison, the broken line shows the change in the degree of moisture, computed according to the equilibrium theory of condensation, assuming the absence of supercooling. It is clear from Figure 4 that there is a substantial difference between the variation laws of the theoretical and observed moisture content in the initial stage of the condensation process. According to the experiment, the greatest change in the moisture content (dy/dl) takes place in the zone of the highest growth rate of the drops, l - 0-10 mm. It is in this range that the characteristic step $K - K'$ is observed on the pressure curve (Fig. 2).

In a qualitative sense the obtained experimental results agree fully with conclusions of the classical theory of nuclear condensation of supercooled steam. In particular there is a good correlation between our results and the calculations made according to the system of equations presented in references [6, 7].

Quantitatively there is satisfactory agreement in the number of drops formed in condensation per unit volume of steam. Thus, for the parameters shown in Figure 4, the experimentally determined number of particles z is $2.55 \cdot 10^{12}$ $1/cm^3$, and the number according to the Folmer theory is $1.85 \cdot 10^{12}$ $1/cm^3$.

The laws of the growth of particles in the liquid phase, and consequently also the laws of the precipitation of condensate in the initial stage of the process of spontaneous condensation, determined by theory and obtained experimentally, disagree substantially (Fig. 5).

The Buler formula, obtained on the basis of molecular-kinetic concepts, establishes a linear law for the change in the dimensions of the drops over time

$$\frac{dr}{d\tau}=\frac{C_p\cdot v_{1l}}{h_{lat}\cdot v_{st}}\sqrt{k_s RT}\cdot\frac{T_s-T}{1-\frac{2\sigma}{r}\frac{v_{1l}}{h_{lat}}}, \qquad (7)$$ /32

where C_p and v_{st} are the specific heat and the specific volume of the steam phase respectively, h_{lat} is the latent heat of condensation; T_s is the temperature of the drops equal to the temperature of the steam in a state of supersaturation; K_s is the index of isentropy.

An almost analogous law of the growth of the drops was given in reference [7]. The author began from the conditions of heat transfer in rarefied gases:

$$\frac{dr}{d\tau}=\frac{Cv_{1l}P}{h_{lat}}\cdot\sqrt{\frac{k}{m_B T}}\cdot(T_s-T), \qquad (8)$$

where k is Boltzmann's constant, m_B is the molecular mass; $C = a\sqrt{\frac{2}{\pi}}$; a is the accomodation coefficient, taken from [8] to equal 0.04.

Folmer obtained the following relationship for the time of the quasistationary formation process of one drop of critical dimension:

$$\tau=r\sqrt{2\pi mkT}/P\cdot v_B, \qquad (9)$$

where v_B is the volume of a molecule in the liquid phase.

It follows from Figure 5 that not one of the above mentioned relationships conforms with reality. Curves 2, 3, 4 in Figure 5 were constructed from the corresponding formulas on the assumption that the temperature difference (T_s - T) is constant. The experimentally derived function for the dimension of a drop is roughly a linear function of log τ, while the growth rate of a drop at the start of the condensation process is greater than that determined by (7) - (9). As the time elapsed from the beginning of condensation increases, the rate of change of the dimension of a drop becomes less than the above mentioned relationships would indicate.

An approximation of the experimental curve yields an expression in the form

$$r = r_0 + b \ln \tau, \tag{10}$$

which for a given regime of the nozzle (P_0 = 2.84 bar and t_0 = 168°C) may be expressed as

$$r = r_0 + 4.88 + 0.608 \lg \tau \ (\text{Å}), \tag{11}$$

where we may take for the initial dimension r_0 the dimension of the nucleus, according to (6) equal to 5.22 Å.

The experimentally derived function relating the dimension of the drop to time also allowed us to determine the nature of the decrease in supercooling as the condensation process developed (Fig. 5).

It is clear in this case that supercooling decreases very rapidly: for a time $\tau \approx 10^{-6}$ sec the value of supercooling decreases from 40 to 2°C. With subsequent development of the condensation process the value of supercooling remains practically constant and equal to 1-2°C [we recall that theoretically $(T_s - T) \to 0$°C with $r \to \infty$].

We will now ascertain the validity of our assumption that the number of drops in the condensation process is constant. Analysis of the obtained results (in particular the growth rate of the drops and the decrease in supercooling) allows us to assume that the process of nucleus formation is completed in a very short interval of time $\tau \cong 10^{-8}$ - 10^{-7} sec. Roughly the same result is obtained from the calculations according to the classical formulas for the formation rate of condensation nuclei, proposed by Folmer, Baker and Frankl. In our example, the steam moves an insignificant distance l = 0.1 - 0.01 mm in such a short span of time. Therefore when /32
studying the spontaneous condensation of steam in nozzles we naturally assume that the number of drops is constant in all stages.

In conclusion we note the following. Despite the fact that the method we used in our work allowed us to obtain new experimental data on the mechanism of spontaneous condensation with various operating regimes of the nozzle, nonetheless it is too soon to draw the final conclusions about the kinetics of condensation. It is necessary to investigate a significant number of supersonic channels with various geometric configurations of the flow section in order to formulate reliable and practically convenient analytic functions for describing spontaneous condensation in nozzles.

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